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RESEARCH MEMORANDUM

ACCELERATION OF HIGH-PRESSURE-RATIO SINGLE-SPOOL TURBOJET ENGINE AS DETERMINED FROM COMPONENT PERFORMANCE CHARACTERISTICS

I - EFFECT OF AIR BLEED AT COMPRESSOR OUTLET

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An analytical investigation was made to determine from component performance characteristics the effect of air bleed at the compressor outlet on the acceleration characteristics of a typical high-pressure-ratio single-spool turbojet engine. Consideration of several operating lines on the compressor performance map with two turbine-inlet temperatures showed that for a minimum acceleration time the turbine-inlet temperature should be the maximum allowable, and the operating line on the compressor map should be as close to the surge region as possible throughout the speed range. Operation along such a line would require a continuously varying bleed area.

A relatively simple two-step area bleed gives only a small increase in acceleration time over a corresponding variable-area bleed.

For the modes of operation considered, over 84 percent of the total acceleration time was required to accelerate through the low-speed range; therefore, better low-speed compressor performance (higher pressure ratios and efficiencies) would give a significant reduction in acceleration time.

INTRODUCTION

Studies of turbojet engine requirements for flight in the transonic regime have revealed that a turbojet engine best suited for such flight would have a compressor pressure ratio of about 7 to 10 and a turbine-inlet temperature of about 2000° to 2300° R (ref. 1). However, when a single-spool axial-flow compressor is used in this pressure-ratio range it usually has poor off-design performance, particularly in the low-speed range (50 to 80 percent of design). In this low-speed range the inlet stages operate in a low-efficiency high-angle-of-attack region and

the outlet stages operate in a low-efficiency turbining region (ref. 2). Equilibrium operation of an engine of this type with several exhaust-nozzle areas is described in reference 3. This reference shows that the equilibrium engine operating lines enter the compressor surge region in the intermediate speed range; therefore, some means which permits operation at pressure ratios below compressor surge must be employed to accelerate through this speed range, since the engine will not accelerate through the compressor surge region.

Several methods of improving the acceleration characteristics of such engines are as follows: compressor-outlet and interstage bleed, which change the matching of compressor and turbine and the matching of stages within the compressor; adjustable compressor-inlet guide vanes and stator blades; and adjustable turbine stators. An investigation is being conducted at the NACA Lewis laboratory to evaluate the relative merits of each of the aforementioned methods for improving the acceleration characteristics of such high pressure-ratio single-spool turbojet engines. As part of this investigation, the effect of air bleed at the compressor outlet, which changes the matching of the compressor and the turbine, is analyzed herein, and the following questions are qualitatively answered: 2729

(1) For operating lines on the compressor performance map which are made roughly parallel to the surge line by bleeding varying amounts of air, what is the effect of turbine-inlet temperature on acceleration time?

(2) For constant turbine-inlet temperatures of 2160° and 2500° R, what is the effect on acceleration time of the proximity of variable-bleed operating lines to compressor surge?

(3) If an optimum constant-area bleed is specified to simplify engine control, what is the effect on acceleration time as compared with that of a variable-area bleed?

SYMBOLS

The following symbols are used in this report:

A area, sq in.

c_p specific heat at constant pressure, Btu/(lb)(°R)

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c_v specific heat at constant volume, Btu/(lb)($^{\circ}$R)

f ratio of fuel flow to air flow

g acceleration due to gravity, 32.174 ft/sec^2

I polar moment of inertia, (ft-lb)(sec^2)

J mechanical equivalent of heat, 778.16 ft-lb/Btu

K constant, $60J/2\pi$, (sec)(ft-lb)/(min)(Btu)

M Mach number

N rotative speed, rpm

p static pressure, lb/sq ft

p' stagnation pressure, lb/sq ft

R gas constant, ft-lb/($^{\circ}$R)(lb)

T' stagnation temperature, $^{\circ}$R

w weight flow, lb/sec

α angular acceleration, radians/sec^2

Γ torque, ft-lb

γ ratio of specific heats, c_p/c_v

δ ratio of stagnation pressure to pressure at NACA standard sea-level conditions, p'/p_0

η adiabatic efficiency, percent

θ stagnation temperature ratio, T'/T_0

τ time, sec

ω angular velocity, radians/sec

Subscripts:

0 NACA standard sea-level conditions

1 compressor inlet

2 compressor outlet

3 turbine inlet

4 turbine outlet 2729

5 exhaust nozzle

a accessories

b bleed air

c compressor

cr critical

d design

i idle speed

l leakage

t turbine

PROCEDURE

Mode of engine operation. - In order to evaluate the effect on acceleration time of the proximity to compressor surge, engine operating lines were arbitrarily specified by points of constant percentages of surge pressure ratio on lines of constant speed. Each line so specified required air bleed in varying amounts at the compressor outlet. In figure 1, which shows compressor performance in terms of speed, weight flow, and pressure ratio, percentage of surge pressure ratio is shown to be a fairly good measure of proximity to surge because the specified operating lines are roughly parallel to and equally spaced from the compressor surge line. Also shown in this figure are operating lines representing turbine-inlet temperatures of 2160° and 2500° R for no air bleed between the compressor and the turbine. The mode of engine operation along these specified operating lines was considered to be as follows: zero time was taken as equilibrium engine operation at idle

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speed, approximately 50 percent of design; an instantaneous increase in turbine-inlet temperature T_3' to the specified value and the corresponding bleed necessary to have the compressor operate along one of the specified operating lines was assumed. As the engine speed increased, the bleed area continuously varied to maintain compressor operation along the specified operating line; when an engine speed was reached that no longer required bleed to stay out of compressor surge (84.5 percent design speed at 2160° R and 89.3 percent design speed at 2500° R) air bleed stopped instantaneously and engine operation then proceeded along the lines of constant T_3' until 100 percent of equivalent design speed was attained. In the case where $T_3' = 2500°$ R, the exhaust-nozzle area was then reduced to the value required for equilibrium engine operation at design speed and the design turbine-inlet temperature of 2160° R.

<u>Determination of acceleration times</u>. - Torque and acceleration are related by the following equation:

$$\Gamma = I\alpha = I\frac{d\omega}{d\tau} \tag{1}$$

The following relation is obtained by solving for the time required to achieve a given change in angular velocity and by writing Γ in terms of compressor and turbine torque:

$$\int_{\tau_i}^{\tau_d} d\tau = \int_{\omega_i}^{\omega_d} I \frac{d\omega}{\Gamma_t - (\Gamma_c + \Gamma_a)} = \frac{2\pi}{60} I \int_{N_i}^{N_d} \frac{dN}{\Delta\Gamma} = \frac{2\pi}{60}\frac{IN_d}{100}\int_{\left(\%\frac{N_i}{N_d}\right)}^{100} \frac{d\left(\%\frac{N}{N_d}\right)}{\Delta\Gamma} \tag{2}$$

If the excess torque $\Delta\Gamma$, developed by the turbine over that required to drive the compressor and the accessories, can be expressed as a function of engine speed, equation (2) may be integrated and the time required for a given change in engine speed may be evaluated.

It is characteristic of turbines that torque increases with turbine-inlet temperature and turbine pressure ratio. Two turbine-inlet temperatures were chosen, 2160° and 2500° R: The first value is the design value and the second value is estimated to be the maximum allowable for short intervals of time, 10 to 15 seconds. In order to insure a high turbine pressure ratio, an exhaust-nozzle area of 600 square inches was assumed as the maximum practical value. The general method of matching the compressor and turbine characteristics is the same as that described in reference 3.

In calculating the acceleration times, it was assumed that NACA sea-level conditions existed at the compressor inlet and that the transient component characteristics were the same as the steady-state conditions; in addition, the following assumptions were made:

Ram pressure ratio, p_1'/p_0	1.0
Burner pressure ratio, p_3'/p_2'	0.97
Stagnation pressure loss in tail pipe for $M_5 = 1.0$, p_5'/p_4'	0.97
Fuel air ratio, f	0.02
Leakage between compressor and turbine, w_l/w_c	0.02
Ratio of specific heats for gas flow in turbine and tail pipe, γ	1.32
Torque to drive accessories, Γ_a, ft-lb	3.0
Exhaust-nozzle area, A_5, sq in.	600

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The particular procedure used in calculating bleed areas and acceleration time may be outlined as follows:

(1) Figure 1 shows the variation of the compressor pressure ratio p_2'/p_1' as a function of a weight-flow parameter $(wN/60\delta_2)$ for lines of constant compressor speed. A point on a constant compressor speed line is chosen arbitrarily at some percentage of compressor pressure ratio at surge. Corresponding values of p_2'/p_1' and $wN/60\delta_2$ are read. For given assumptions of fuel-air ratio f, engine leakage w_l/w_c, and burner pressure drop δ_3/δ_2, a value of $w_tN/60\delta_3$ may be calculated from the following equation:

$$\frac{w_tN}{60\delta_3} = \left(1 + f - \frac{w_l}{w_c}\right)\frac{\delta_2}{\delta_3}\,\frac{w_cN}{60\delta_2} \tag{3}$$

This value of $w_tN/60\delta_3$ is the normal weight-flow parameter the turbine would have to have for the compressor to operate at the particular point chosen.

(2) The corresponding value of the torque parameter necessary to drive the compressor and the accessories is shown in figure 2 as a function of the normal turbine weight-flow parameter $w_tN/60\delta_3$ for lines of constant compressor speed. The compressor torque parameter $\Gamma_c/\delta_3 + \Gamma_a/\delta_3$ for the particular point is determined by the compressor speed and the calculated weight-flow parameter $w_tN/60\delta_3$ (eq. (3)).

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(3) The variation of the turbine torque parameter is shown in figure 3 as a function of $w_t N/60\delta_3$ for lines of constant turbine speed and pressure ratio. When the compressor speed and the turbine-inlet temperature are known, the equivalent turbine speed may be determined from the following equation:

$$\frac{T_3'}{T_1'} = \frac{\left(\% \frac{N}{N_d}\right)_c^2}{\left(\% \frac{N}{N_d}\right)_t^2} \left(\frac{T_3'}{T_1'}\right)_d \tag{4}$$

(4) A trial-and-error solution for the turbine torque parameter is now required. Several values of Γ_t/δ_3 are chosen and the corresponding values of $w_t N/60\delta_3$ and p_3'/p_4' are read from the line of constant equivalent design speed $(N/N_d)_t$ (fig. 3).

(5) These values of $w_t N/60\delta_3$ and p_3'/p_4' and the known compressor pressure ratio are then used to calculate p_4', T_4', and w_t from the following equations:

$$\frac{p_4'}{p_0} = \frac{p_2'}{p_0}\frac{p_3'}{p_2'}\frac{p_4'}{p_3'} \tag{5}$$

$$\frac{T_4'}{T_3'} = 1 - \frac{\Gamma_t N}{K w_t c_p T_3'} \tag{6}$$

$$w_t = \frac{w_t N}{60\delta_3}\left(\frac{60\delta_3}{N}\right) \tag{7}$$

The exhaust-nozzle area is then calculated as described in reference 3 and plotted against p_3'/p_4'. The value of p_3'/p_4' corresponding to the assumed value of A_5 (600 sq in.) is thus determined. This value together with the known $(N/N_d)_t$ specifies Γ_t/δ_3 and $w_t N/60\delta_3$. The $\Delta\Gamma$ is thus determined and, from the difference between the compressor value of $w_t N/60\delta_3$ and the turbine value of $w_t N/60\delta_3$, the amount of air bleed necessary to have this operating condition exist in the engine is calculated.

(6) A graphical integration of equation (2) is obtained by plotting $1/\Delta\Gamma$ against N/N_d in percent for a given percentage of surge pressure ratio and constant turbine-inlet temperature. A typical example, for 100 percent surge pressure ratio and $T_3' = 2500^\circ$ R, is shown in figure 4.

(7) For the case of constant-area bleed, the effective critical area for each compressor operating point is calculated from the following equation:

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$$A_{cr,b} = \frac{144\ w_b \sqrt{T_2'}}{p_2'}\sqrt{\frac{R}{\gamma g}}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{8}$$

where $A_{cr,b}$ is the bleed area corresponding to the bleed weight flow w_b and sonic bleed velocity. In cases where p_2'/p_0 is less than critical, values of the critical area ratio A/A_{cr} corresponding to the pressure ratios in question were used to calculate actual bleed areas.

Bleed areas thus calculated were plotted against the percentage of surge pressure ratio for lines of constant compressor speed for turbine-inlet temperatures of 2160° and 2500° R. One of the bleed areas chosen is the minimum constant value that will allow compressor operation at or below surge for all engine speeds. This area is held constant and the corresponding percentage of surge p_2'/p_1' is determined for other engine speeds. With the compressor operating point thus specified, the values of $\Delta\Gamma$ and the acceleration time are calculated as outlined in steps (1) through (6). Acceleration times for other constant values of bleed area were calculated in the same manner.

RESULTS AND DISCUSSION

Acceleration with variable-area bleed. - The calculated acceleration times are presented in figure 5 where time in seconds is plotted against percentage of equivalent design speed for operating lines of constant percentage values of surge pressure ratio for the two specified turbine-inlet temperatures, 2160° and 2500° R. A minimum time of 5.5 seconds was obtained for operation along the surge line at $T_3' = 2500^\circ$ R. In every case, more than 84 percent of the total acceleration time is required in the low-speed region, from 50 to 80 percent design speed. Therefore, a significant decrease in acceleration time may be obtained by improving the operating characteristics of the compressor and the turbine at low engine speeds.

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A plot of total acceleration time against percentage of surge pressure ratio for lines of constant T_3' is presented in figure 6. Here it is evident that the required time increases rapidly for values of surge pressure ratio below 97 percent for turbine-inlet temperatures of 2160° and 2500° R, particularly for the lower temperature. The higher temperature results in a lower acceleration time for each operating line specified; at 98 percent of surge pressure ratio, the acceleration time at 2500° R was 30 percent lower than at 2160° R. It may be concluded that operation near compressor surge is necessary if a minimum acceleration time is required. Consequently, an engine control system that senses incipient surge would be useful in obtaining minimum acceleration time.

Acceleration with constant area bleed. - As pointed out previously, bleed area was continuously varied for the specified type of engine acceleration. This area variation is plotted in figure 7 against percentage of equivalent engine design speed for lines of constant percentage surge pressure ratio and turbine-inlet temperatures of 2160° and 2500° R. It is reasonable to suppose that a control to obtain this area variation would necessarily be complicated. Consequently, the acceleration time with a less complicated constant-area bleed was calculated.

As indicated in figure 7(b) several relatively simple area variations were considered. The first (case I) was a constant area at a value which is required for 100 percent surge pressure ratio at approximately 79.5 percent design speed (23.4 sq in.). The second (case II) was the constant area which is required for 98 percent surge pressure ratio at 77.5 percent design speed (28.6 sq in.). The third (case III) was a two-step area variation. The area was constant at 15 square inches to 68.5 percent design speed, at which speed operation was at surge; the area instantaneously increased to 23.4 square inches, which is the surge-line bleed area at 79.5 percent design speed and was held constant at this value to 89.3 percent design speed. The operating line specified by this third area variation, then, lies near the surge line touching at 68.5 and 79.5 percent design speed. The fourth (case IV) was similar to case III, lying near the 98 percent surge pressure ratio line and touching it at two speeds. Similar area values for a turbine-inlet temperature of 2160° R would have little significance, because there is still freedom to use higher values of T_3'.

Acceleration times for cases I through IV are presented in figure 8 where acceleration time in seconds is plotted against percentage equivalent design speed. Cases I and II give total acceleration times of 8.7 and 22.5 seconds, respectively. These two cases would have the simplest control mechanism; however, case II may be eliminated because

of the excessive time required for acceleration. Case I, on the other hand, gave an acceptable acceleration time but the engine would operate right at surge at 79.5 percent design speed. Therefore, without some means of sensing surge, there would be danger of surging the engine. The same statement may be made for case III which would allow the engine to operate at incipient surge at two speeds. Case IV gave an acceptable acceleration time and the engine would operate at 98 percent of surge at only two speeds (68 and 77.5 percent equivalent design speed); this would give a small margin of safety from the standpoint of compressor surge. The total acceleration time for case IV is 7.8 seconds which was only 1.2 seconds longer than acceleration along the 98 percent surge pressure ratio line and had the advantage of simpler control. It appears, then, that a two-step area variation such as case IV is the best compromise among the modes of acceleration considered.

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SUMMARY OF RESULTS

An investigation of the effects of air bleed at the compressor outlet on the acceleration characteristics of a typical high-pressure-ratio single-spool turbojet engine produced the following results.

1. For the two turbine-inlet temperatures considered, 2160° and 2500° R, the higher value gave a shorter acceleration time for any specified operating line. Acceleration time at the higher temperature was 30 percent less than that at the lower temperature for operation at 98 percent of surge pressure ratio.

2. Minimum acceleration time was obtained with a turbine-inlet temperature of 2500° R and variable bleed-area operation along the surge line on the compressor map.

3. Acceleration time increased rapidly as the specified operating lines moved away from the compressor surge region (that is, to lower values of percentage surge pressure ratio).

4. Specification of a constant-area bleed gave large increases in acceleration time over that required for the corresponding variable-area case.

5. A relatively simple two-step area control gives only small increases in acceleration time over the corresponding variable-area case.

6. Over 84 percent of the total acceleration time for all modes of acceleration investigated was required in the low-speed range (50 to 80 percent design speed). Better low-speed compressor performance (higher pressure ratios and efficiencies) would therefore give a significant reduction in acceleration time.

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2. Medeiros, Arthur A., Benser, William A., and Hatch, James E.: Analysis of Off-Design Performance of a 16-Stage Axial-Flow Compressor with Various Blade Modifications. NACA RM E52L03, 1953.

3. Rebeske, John J., Jr., and Dugan, James F., Jr.: Matched Performance Characteristics of a 16-Stage Axial-Flow Compressor and a 3-Stage Turbine. NACA RM E52H18, 1952.

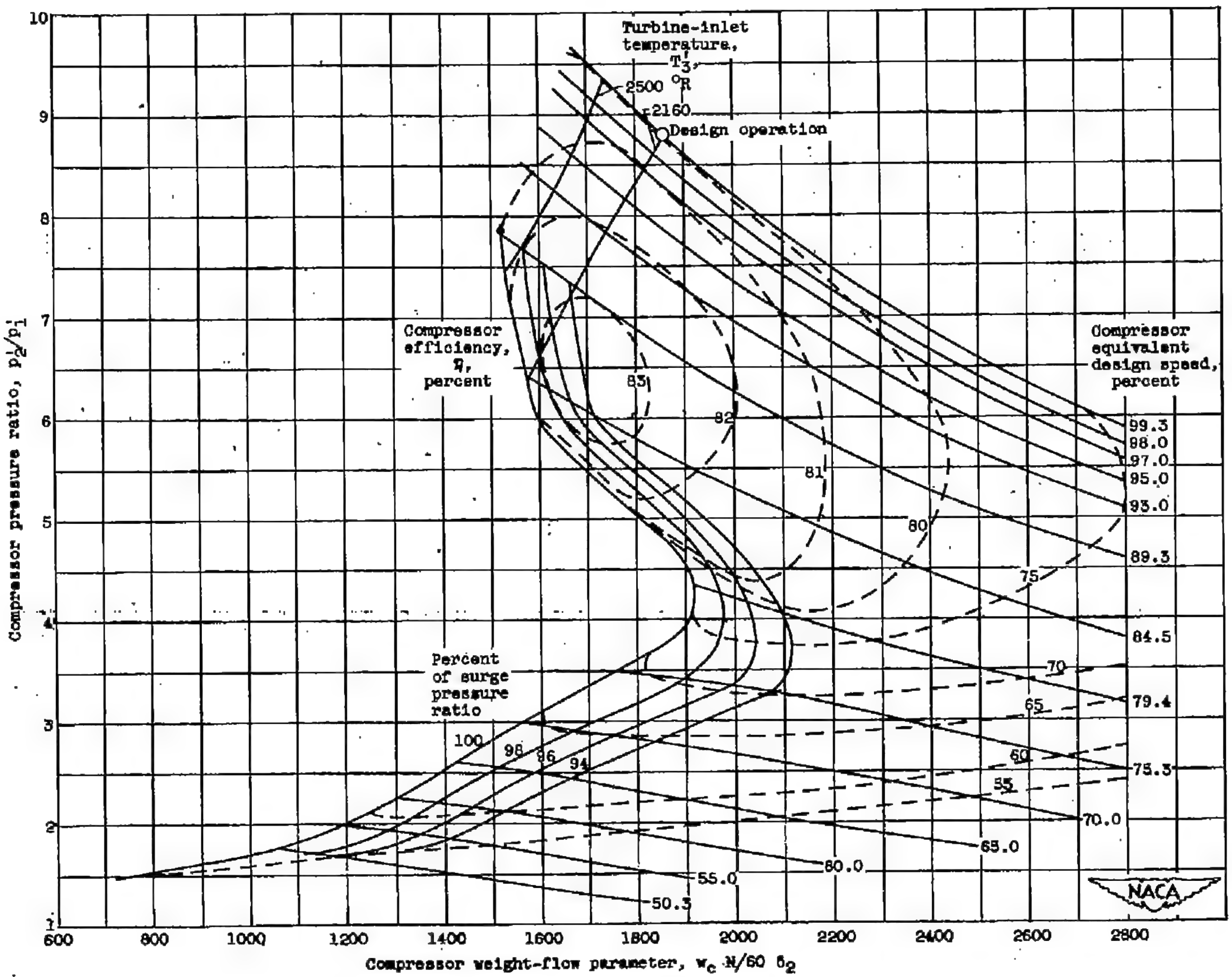
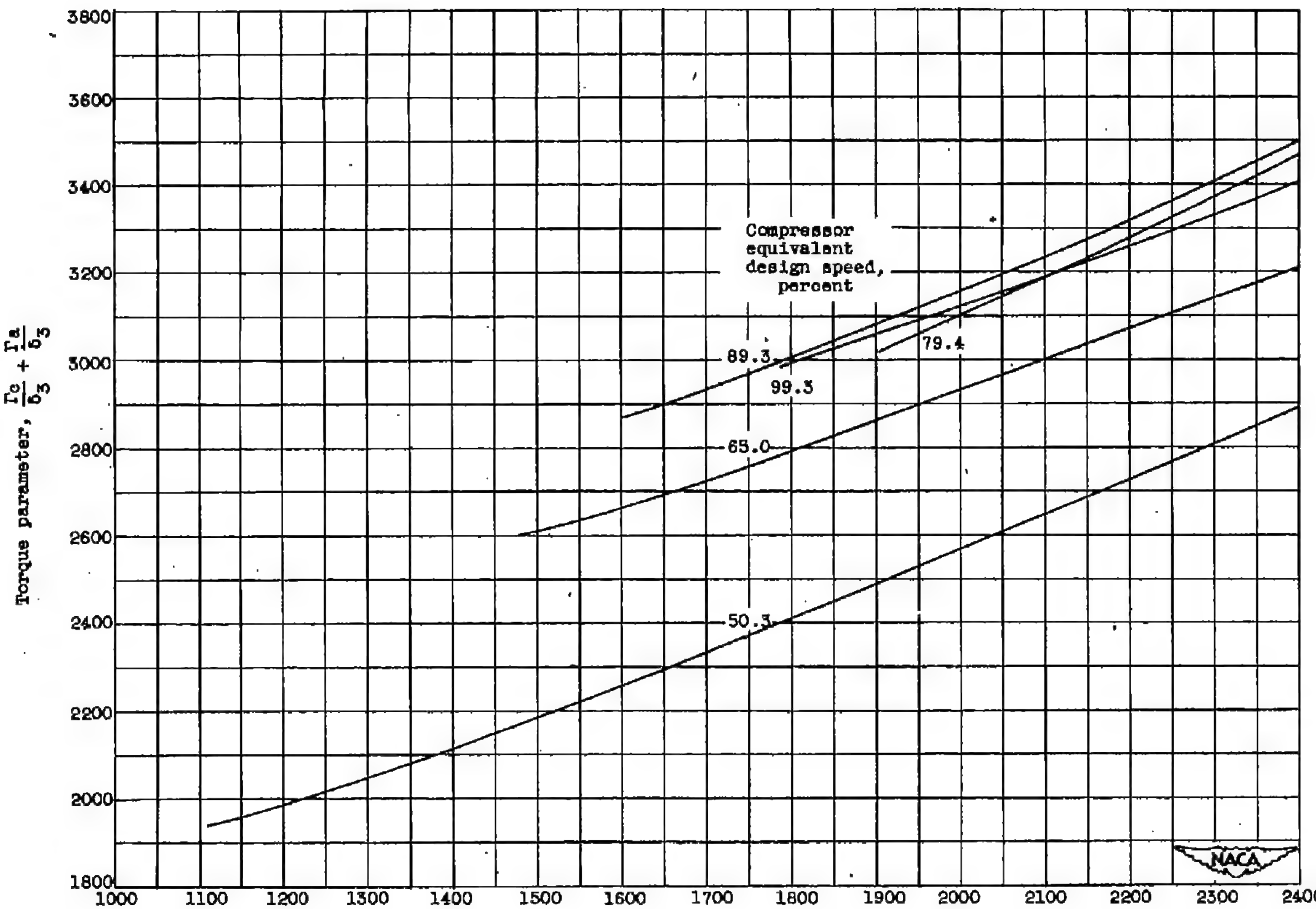


Figure 1. - Compressor performance map.



Flow parameter, $\frac{w_c N}{60\ \delta_2}\left[\frac{\delta_2}{\delta_3}\left(1 + f - \frac{w_l}{w_c}\right)\right]$

Figure 2. - Compressor torque characteristics.

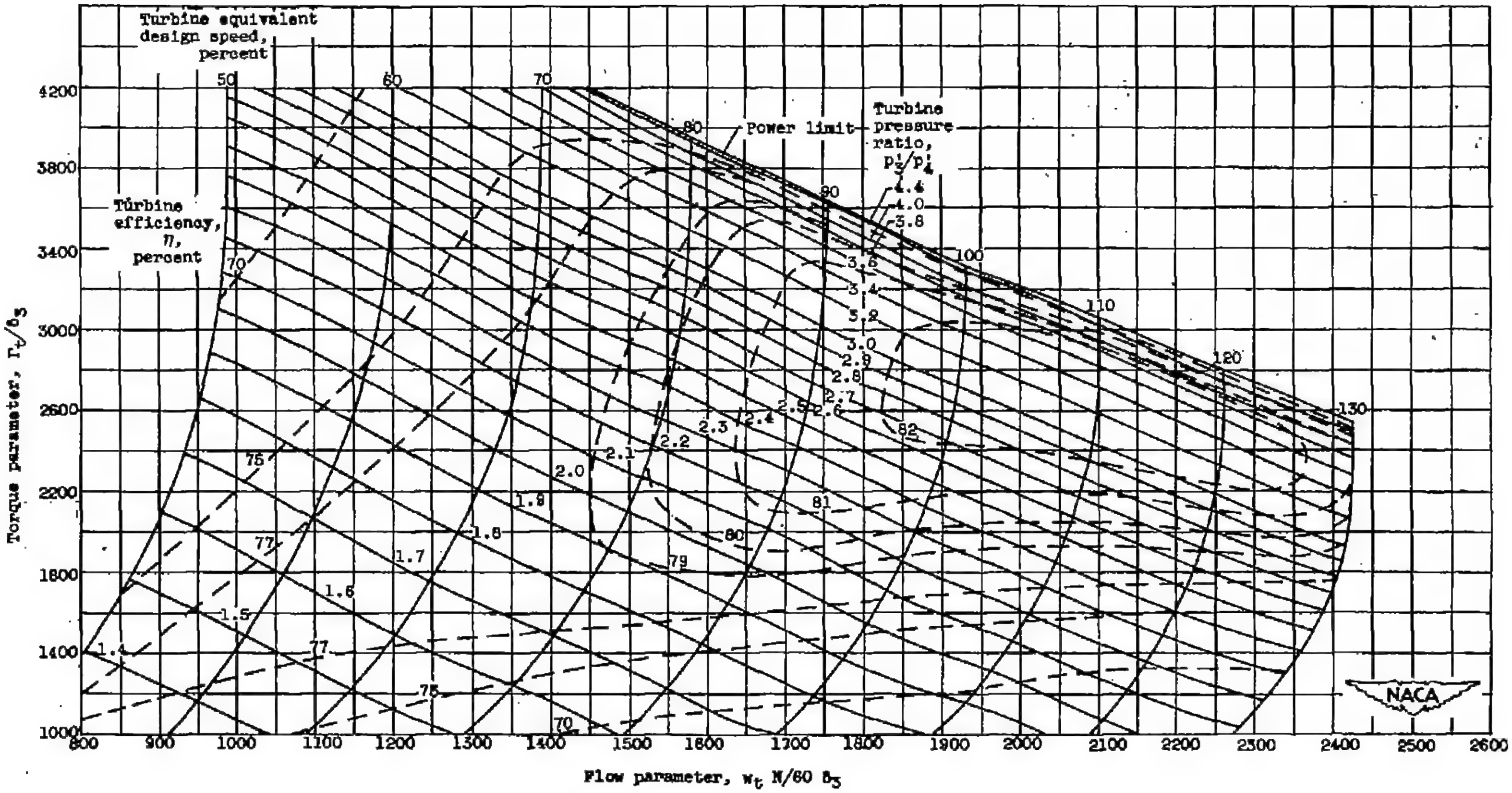


Figure 3. - Turbine performance map.

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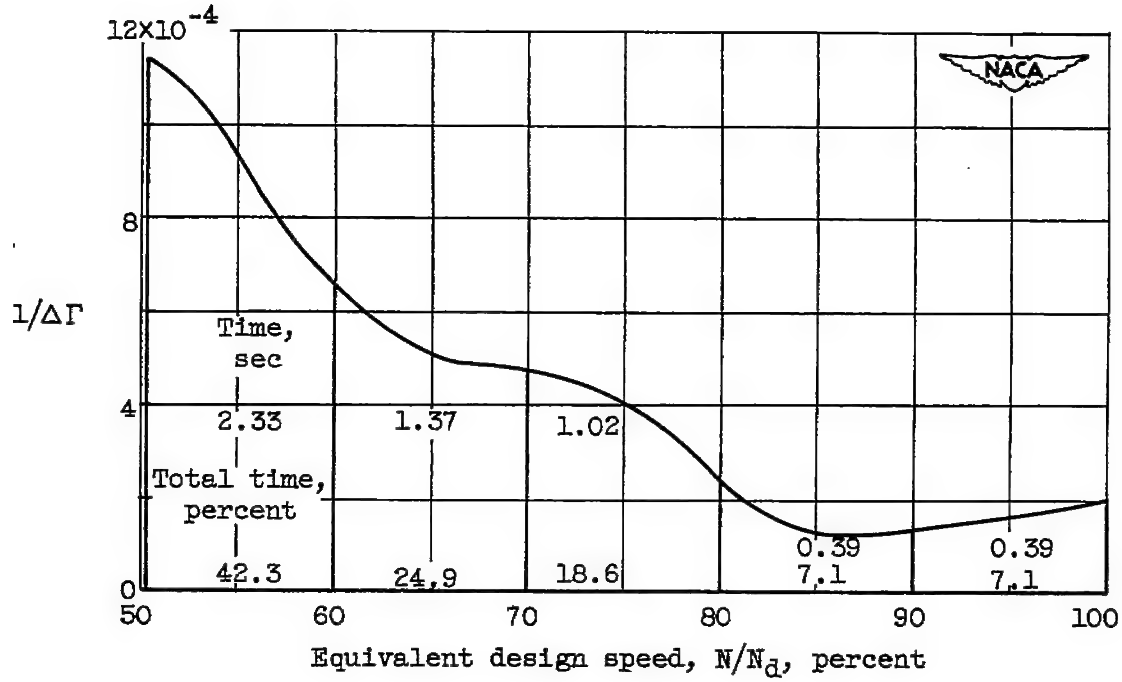

Figure 4. - Graphical integration for acceleration time. Turbine-inlet temperature T_3, 2500° R; 100 percent surge pressure ratio.

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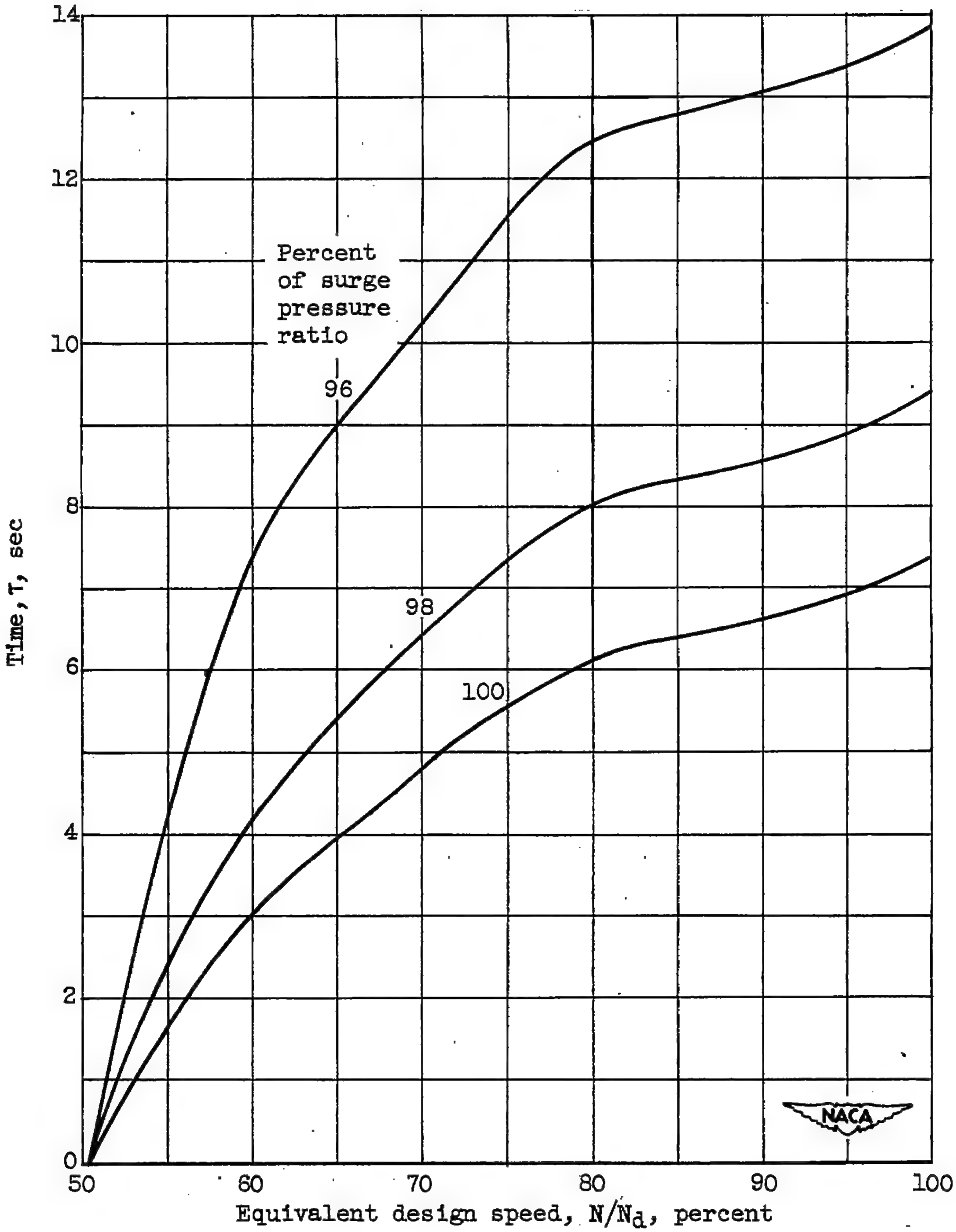
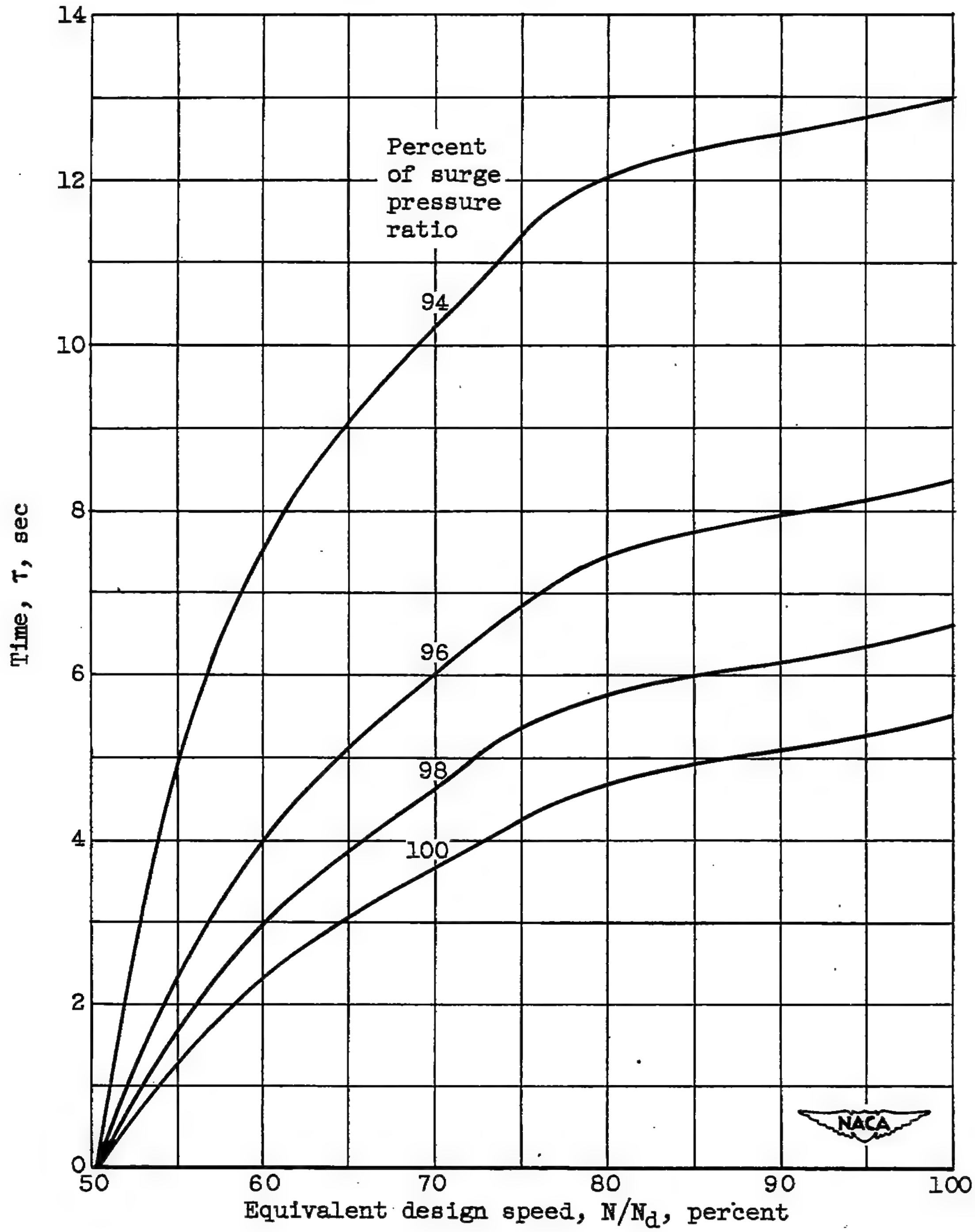


(a) Turbine-inlet temperature, 2160° R.

Figure 5. - Calculated acceleration time for constant percentages of surge pressure ratio.



(b) Turbine-inlet temperature, 2500° R.

Figure 5. - Concluded. Calculated acceleration time for constant percentages of surge pressure ratio.

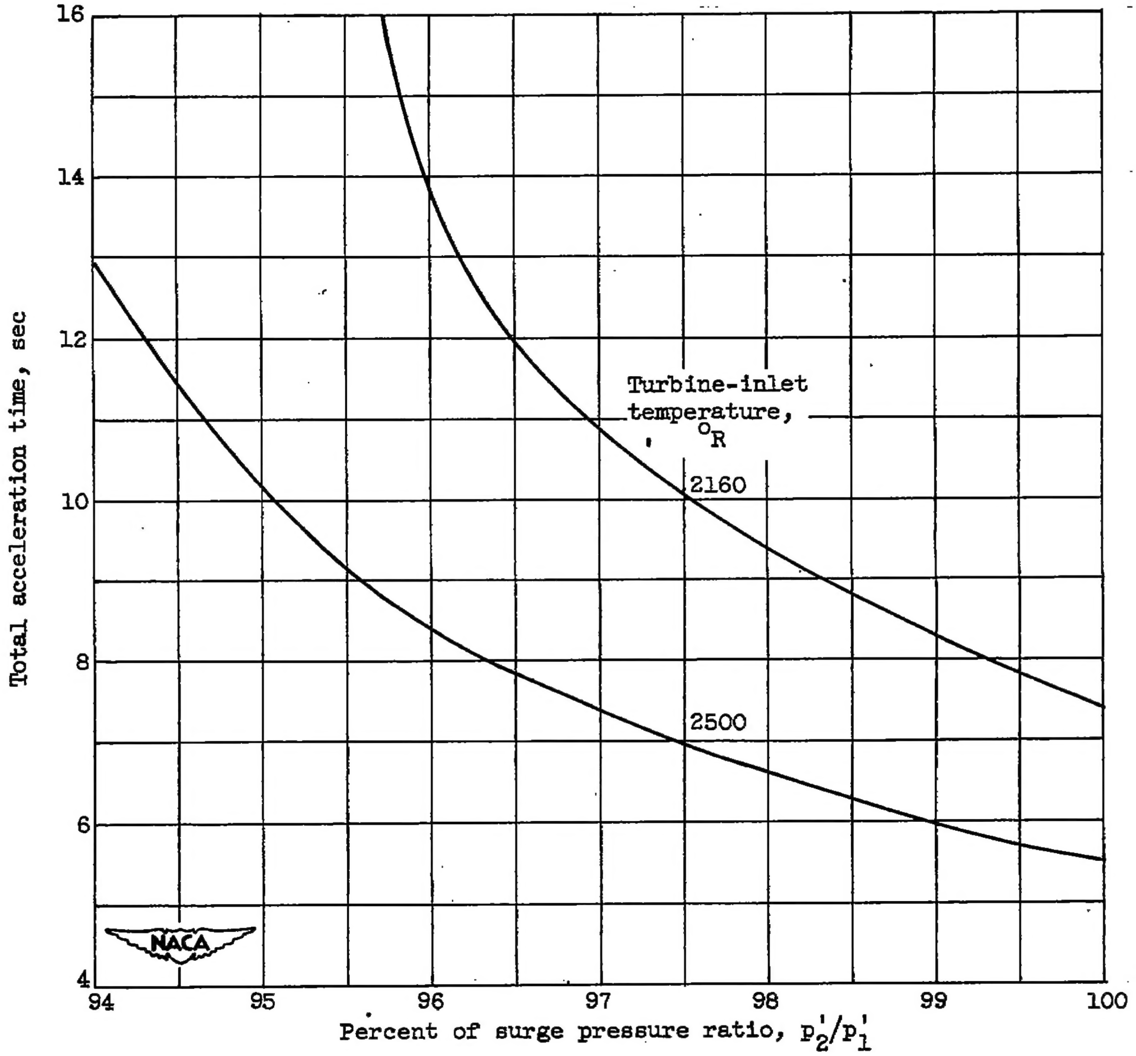
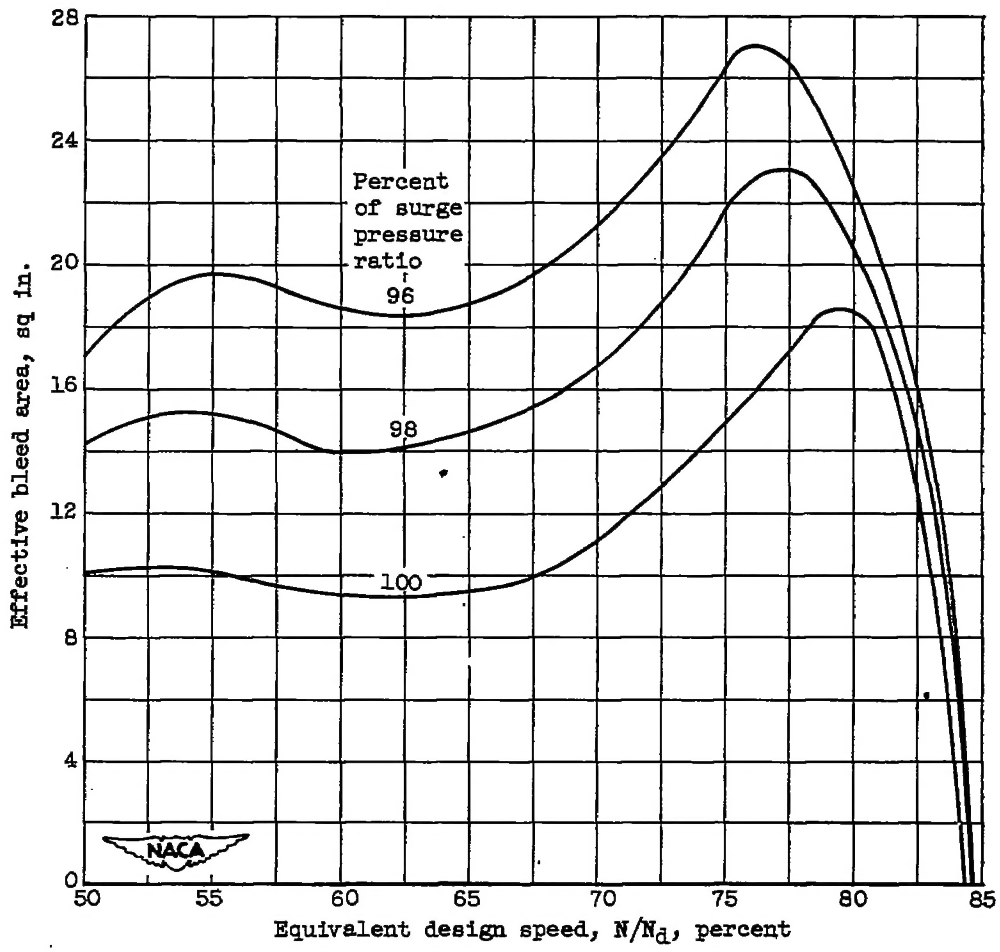
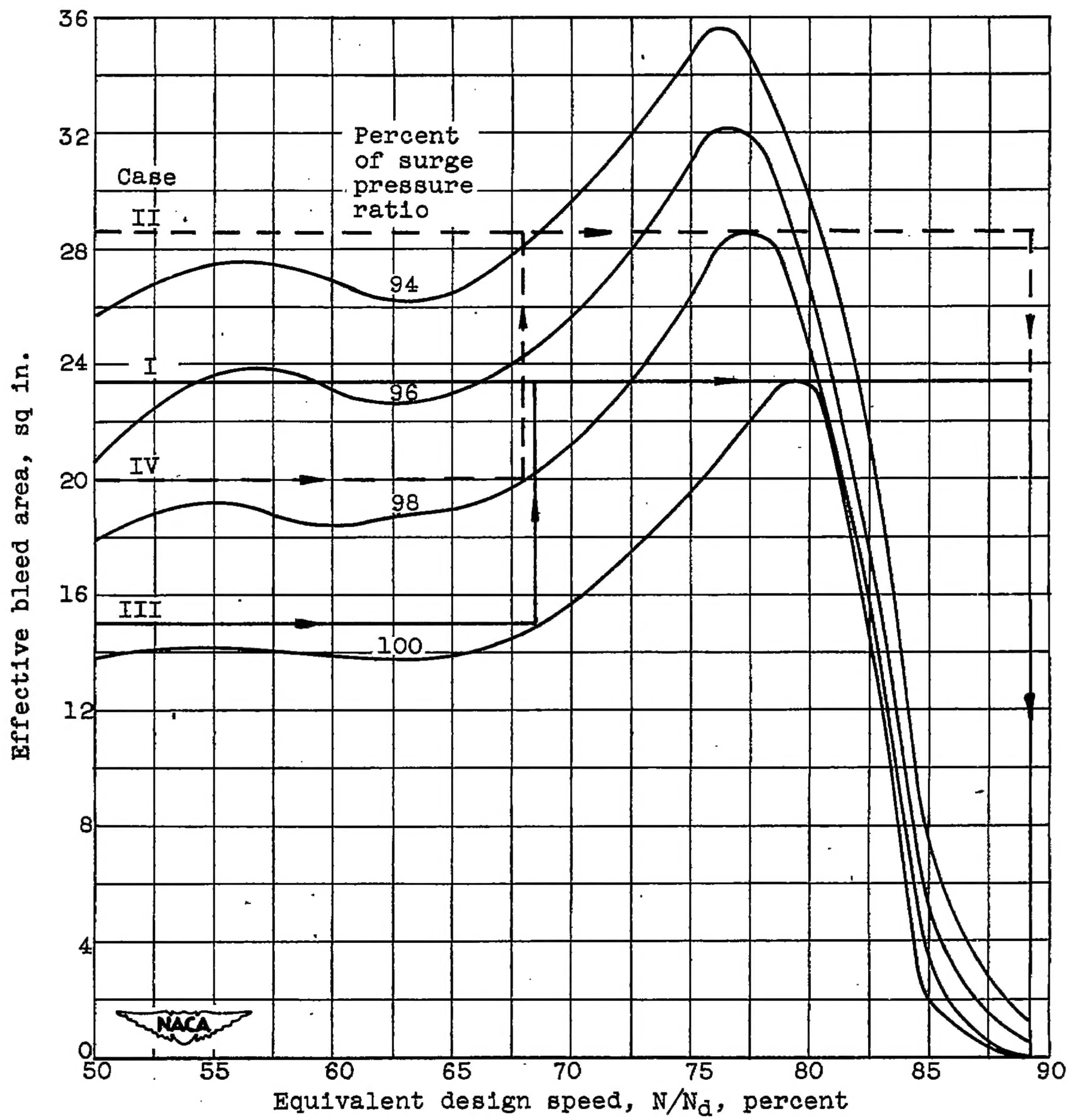


Figure 6. - Total acceleration time for constant values of turbine-inlet temperature.



(a) Turbine-inlet temperature, 2160° R.

Figure 7. - Variation of effective bleed area with speed for several specified operating lines.



(b) Turbine-inlet temperature, 2500° R.

Figure 7. - Concluded. Variation of effective bleed area with speed for several specified operating lines.

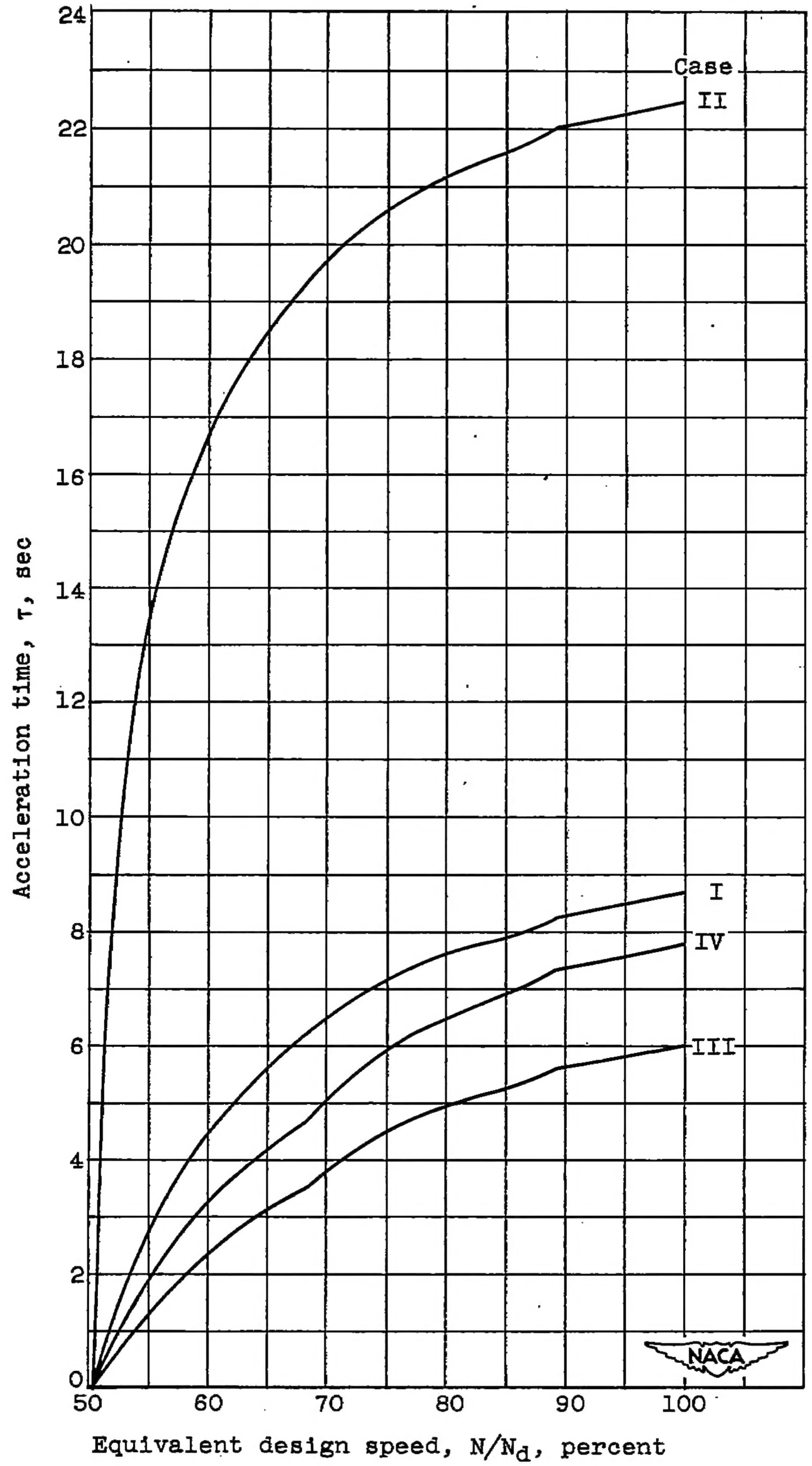


Figure 8. - Acceleration time for constant-area bleed.

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